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Unidentified EGRET Sources and the Extragalactic Gamma-Ray Background

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Abstract The large majority of EGRET point sources remain to this day without an identified low-energy counterpart. Whatever the nature of the EGRET unidentified sources, faint unresolved objects of the same class must have a contribution to the diffuse gamma-ray background: if most unidentified objects are extragalactic, faint unresolved sources of the same class contribute to the background, as a distinct extragalactic population; on the other hand, if most unidentified sources are Galactic, their counterparts in external galaxies will contribute to the unresolved emission from these systems. Understanding this component of the gamma-ray background, along with other guaranteed contributions from known sources, is essential in any attempt to use gamma-ray observations to constrain exotic high-energy physics. Here, we follow an empirical approach to estimate whether a potential contribution of unidentified sources to the extragalactic gamma-ray background is likely to be important, and we find that it is. Additionally, we comment on how the anticipated GLAST measurement of the diffuse gamma-ray background will change, depending on the nature of the majority of these sources.

Keywords Gamma rays: observations · Gamma-ray sources: astronomical · Radiation sources: unidentified

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1 Introduction

The EGRET telescope aboard the *Compton Gamma-Ray Observatory* detected, during its nine years of operation, not only 271 point sources [1] but also diffuse emission [2,3]. Based on the origin of the diffuse photons, we can classify this emission as Galactic if it is produced within the Milky Way, or as extragalactic if it originates from larger, cosmological distances. The two types of emission can be identified, to a certain extent, from their spatial distribution: Galactic emission is expected to be enhanced near the Galactic plane, while extragalactic emission is expected to be largely isotropic – however, the Galactic emission does not quickly fall off to zero as we move away from the plane. Disentangling the Galactic and extragalactic components requires modeling the Galactic emission through cosmic ray propagation models (e.g. [2,6]) and subtracting it from the all-sky diffuse signal. The uncertainties involved in this process are nontrivial. Residuals from inadequate or imperfect treatment of the dominant Galactic component can severely contaminate the determination of the extragalactic emission [4,5,6].

Diffuse emission can also be characterized, depending on the process by which it is produced, as truly diffuse or as unresolved point source emission. Truly diffuse is, for example, the emission resulting from cosmic ray interaction with interstellar matter in the Milky Way¹, as well as the emission from particles accelerated in shocks at the outskirts of cosmological large-scale structures. In contrast, unresolved point source emission is the emission produced by a collection of faint, unresolved point sources such as blazars, perceived as diffuse due to limitations in telescope sensitivity.

Although many sources have been suggested to be the origin of the diffuse emission, there are some *guaranteed*

¹ Note however that enhanced emission close to cosmic-ray sources could in principle be resolved as point source emission and would thus count as “unresolved point source emission” in this classification scheme.

contributions. Any known class of gamma-ray sources with some already identified members must have at least some contribution to diffuse emission. This would originate from the collective emission from fainter members, unresolved by EGRET. Prime examples of such classes are blazars, which may be a dominant component of the extragalactic diffuse emission, e.g. [7,8,9,10], as well as normal galaxies, e.g. [11,12], or pulsars (for the case of the Galactic diffuse emission), e.g. [13,14,15].

It is also possible that unresolved sources of the same class as unidentified EGRET sources have some appreciable contribution to the extragalactic background. Although their nature remains unknown, it is reasonable to believe that there is a large number of fainter, unresolved objects of the same class, making some contribution to the diffuse emission. In addition, unidentified sources are the most numerous group of gamma-ray sources. If they represent yet unidentified members of some known class of gamma-ray emitters (e.g. blazars), then excluding them from any calculation of the contribution of the parent class to the diffuse background would lead to a significantly underestimated result, due to an incorrect normalization of the bright-end of the gamma-ray luminosity function. If they represent an unknown class of gamma-ray emitters (which is likely – see e.g. [16]), then the contribution of their unresolved counterparts to the diffuse emission would significantly limit the diffuse flux left to be attributed to known classes and to truly diffuse emission.

Similarly, investigating the diffuse emission from unresolved unidentified objects is important regardless of the location of these objects (whether they are Galactic or extragalactic). If they are extragalactic, then unresolved objects of the same class contribute to the diffuse extragalactic gamma-ray background. Alternatively, if they are all Galactic, objects of the same class in other unresolved galaxies enhance the contribution of their hosts to the gamma-ray background².

Hence, some contribution of unresolved unidentified sources to the extragalactic diffuse background is certain. It is therefore clear that until we either (a) resolve the issue of the nature of unidentified sources or (b) derive some strong constraint indicating that a possible contribution of such unresolved objects would indeed be minor, we cannot hope to be confident in our understanding of the origin of the extragalactic gamma-ray background. However, predictions for the level of their collective contribution involve important uncertainties: due to lack of identification of low-energy counterparts, we have no estimates of distance, and therefore no estimates of the gamma-ray luminosities of these sources. For this reason, very few constraints can be placed on their cosmic distribution and evolution.

In this work, we approach the problem from a purely empirical point of view. Instead of attempting to *predict* the level of a diffuse component due to unresolved objects of the same class as unidentified EGRET sources, we try to assess whether there are any quantitative indications that this component is, in fact, minor. Under the assumption that the majority of the unidentified EGRET sources can be treated as members of a single class of gamma-ray emitters, and for the case that this class consists of *extragalactic objects*, we try to answer the following two questions: (1) is it likely that unresolved objects of the same class could have a significant contribution to the extragalactic gamma-ray background at least in some energy range, and (2) how would the collective spectrum of their emission compare to the measured spectrum of the extragalactic gamma-ray background deduced from EGRET observations. The observational input constraining our calculations will be the number distribution of unidentified sources with respect to flux, and the spectral index of each source. We also examine how we expect GLAST observations to change our knowledge of the nature of unidentified sources, based on the insight gained from our analysis.

This paper is structured as follows. In §2 we summarize the formalism used to derive the extragalactic gamma-ray background component due to unresolved unidentified sources under our set of assumptions. In §3 we describe our results and their implications. Prospects for the GLAST era are discussed in §4. Finally, we conclude and discuss our findings in §5.

2 Formalism

In this section, we describe how we can use the flux distribution of unidentified sources to extract information about a possible contribution of unresolved sources of the same class to the extragalactic diffuse gamma-ray background. The assumptions we will make to proceed are that (a) the unidentified sources can indeed be viewed as a class of objects, so that constructing a flux distribution is meaningful³; and (b) close to the EGRET flux limit, the flux distribution does not evolve drastically so that an extrapolation of the measured flux distribution to lower fluxes is representative of its behavior in the low-flux regime. This assumption is less likely to hold as the limiting flux to which we are extrapolating becomes lower: the flux distribution *will* eventually exhibit a break due to cosmological effects and/or luminosity evolution.

The question we will seek to answer is how far in the low-flux regime our extrapolation must continue before we get a significant contribution of unresolved unidentified sources to the gamma-ray background. If the answer

² Additionally, unresolved sources of the same class in our own galaxy contribute to the diffuse emission of the Milky Way.

³ In reality, even if most of the unidentified sources do belong to the same class, there is always going to be some contamination of different class objects; however, it is conceivable that such contamination is small.

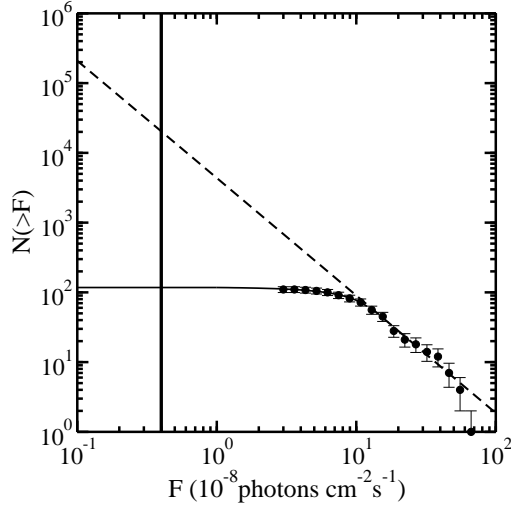


Fig. 1 Flux distribution of unidentified sources. The error bars represent 1σ Poisson errors. Dashed line: power-law fit in the range $13 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \leq F \leq 55 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. Solid line: parabolic fit in the range $3 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \leq F \leq 13 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. Thick solid line: F_{\min} .

is “not very far”, then we might expect that the actual flux distribution of the unresolved sources does indeed resemble our assumed form and that unresolved, unidentified sources make up a considerable fraction of the extragalactic diffuse background. On the other hand, if we need to extrapolate the flux distribution down to fluxes very low compared to the resolved flux range, then it is quite unlikely that our extrapolation is valid throughout the flux regime we are using it. In such a case it is doubtful that the actual flux distribution of the unresolved unidentified sources is indeed such that unidentified sources make up a significant portion of the extragalactic diffuse background.

2.1 The cumulative flux distribution

In our calculation, we will only include in the “unidentified object” class those 3rd EGRET catalog sources which still remain without a suggested low-energy counterpart candidate⁴. If any sources originally included in the 3rd EGRET catalog listing of unidentified sources have been omitted when they should in fact have been included in our object sample, the error that this omission incurs is consistently toward the side of *underestimating* the importance of the contribution of uniden-

tified sources to the diffuse background. The opposite extreme would be if we had chosen to include all sources marked as unidentified in the 3rd EGRET catalog. Including *more* sources in the resolved sample than we did, would significantly enhance the bright-end of the flux distribution; this would also imply more faint-end, unresolved, unidentified sources, which would support a stronger unidentified source component in diffuse radiation. In a future version of this work, we plan to assess quantitatively the uncertainties introduced by our choice of the “unidentified sources” sample by examining to what extent our conclusions may change when different sets of EGRET sources, satisfying different criteria, are used.

The cumulative flux distribution, $N(> F)$ (number of sources with flux above F versus F) of these sources is plotted in Fig. 1. Here, F is the mean⁵ (P1234) photon flux in energies above 100 MeV quoted in the 3rd EGRET catalog [1]. The dashed line is the power-law fit to the data in the flux interval between $13 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ and $55 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$, $N_b(> F) = CF_8^{-\kappa}$, with $F_8 = F/(10^{-8} \text{ cm}^{-2} \text{ s}^{-1})$, $\ln C = 8.32 \pm 0.36$ and $\kappa = 1.67 \pm 0.11$. In the “faint source” end of the cumulative flux distribution, the data necessarily deviate from the power law fit due to the finite sensitivity of the telescope. However, because of differences in sky coverage, the angular dependence of the diffuse background, and source variability, there is no sharp cutoff in the fluxes of resolved objects. Instead, the cumulative flux distribution gradually flattens. The thin solid line shows a polynomial fit to the data in the faint source end (flux interval between $3 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ and $13 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$), $N_f(> F) = A_0 - A_1 F_8 - A_2 F_8^2$, with $A_0 = 119.5$, $A_1 = 1.837$ and $A_2 = 0.24214$. The subscripts b and f in $N(> F)$ refer to the “bright” and “faint” end of the cumulative flux distribution respectively.

If an extrapolation of the power law fit to low fluxes is representative of the number of existing sources in the faint source end, then the *differential* flux distribution (number of objects with fluxes between F and $F + dF$) of existing sources (both resolved and unresolved) of the “unidentified class” in units of $(10^{-8} \text{ cm}^{-2} \text{ s}^{-1})^{-1}$ is $|dN/dF|_b = \kappa C F_8^{-\kappa-1}$. In the faint end of source fluxes, the number of *unresolved* sources with fluxes between F and $F + dF$ is the number of existing sources minus the number of resolved sources, or

$$\left| \frac{dN}{dF} \right|_u dF = dF_8 [\kappa C F_8^{-\kappa-1} - A_1 - 2A_2 F_8] . \quad (1)$$

2.2 The spectral index distribution

The second important observational input in our calculation is the distribution of spectral indices of unidentified objects. In our analysis we will adopt the assumption

⁵ Note that we have not tried to address strong variability of the sources.

⁴ Sample compiled and actively maintained by C. Brown and available online at http://home.uchicago.edu/~carolynb/unidentified_sources. It is important to note that suggested associations with lower-energy counterparts included in this compilation are simply results reported in recent publications; no effort was made to evaluate the significance and validity of these counterparts by a single uniform standard.

that the spectral index distribution of unresolved unidentified sources is the same as that of the resolved unidentified sources. The latter can be deduced from measurements of the spectral index α for each of the resolved unidentified sources.

Figure 2 shows a histogram of the spectral indices of the resolved unidentified sources (solid line). Note that the typical measurement uncertainty for any single spectral index (thick solid line) is comparable with the spread of the distribution, so that the spread of a simple binning of spectral indices might not in fact give us information about the underlying distribution of the spectral indices of the sources, but rather be representative of the uncertainty of each single measurement. This problem is not unique to unidentified sources. It is also a problem in measuring the spectral index distribution of blazars, where the usually derived concavity [7] of the collective unresolved blazar spectrum may simply be the result of overestimating the spread in the spectral index distribution [17].

Following an analysis similar to that of [17] for the case of blazars, we assume that the intrinsic spectral index distribution of unidentified sources can be approximated by a gaussian. We then use a maximum-likelihood analysis which takes into account the individual errors of measurement of α for each source⁶ to estimate the parameters of the distribution, obtaining a mean of $\alpha_0 = 2.38 \pm 0.03$ and a standard deviation of $\sigma_\alpha = 0.19 \pm 0.03$. The errors quoted are 1σ uncertainties of each parameter with the other fixed at its maximum-likelihood value. The maximum-likelihood distribution is plotted with the dashed line in Fig. 2, and is narrower and displaced to lower spectral indices with respect to the histogram (a result reflecting the fact that sources with higher values of α also tend to have a larger error of measurement in α). However, due to the large systematics associated with the observational determinations of the extragalactic gamma-ray background spectrum at high energies, our conclusions are not very sensitive to the small displacement of the peak.

2.3 Contribution to the extragalactic gamma-ray background

The extragalactic gamma-ray background is described by the differential photon intensity I_E (photons per unit area-time-energy-solid angle). Each unresolved source of flux F has a contribution $I_{E,1}(F)$ to the diffuse emission which is given by

$$I_{E,1}(F) = (\alpha - 1) \frac{F}{4\pi E_0} \left(\frac{E}{E_0} \right)^{-\alpha}, \quad (2)$$

where α is the spectral index of the source, and $E_0 = 100$ MeV is the lowest photon energy included in the

⁶ We do this by introducing the true spectral indices of the sources as nuisance parameters and by marginalizing over them.

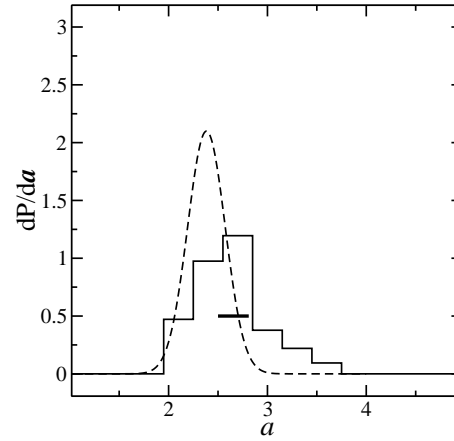


Fig. 2 Spectral index distribution of unidentified sources. Solid line: histogram of the EGRET data. Dashed line: maximum-likelihood gaussian. Thick solid line: typical uncertainty of individual spectral index determination using EGRET data.

measurement of F . The $1/4\pi$ normalization factor comes from assuming an isotropic distribution of sources, the collective emission of which is uniformly distributed over the celestial sphere. Using Eq. (1) for the distribution of fluxes, the maximum-likelihood gaussian of §2.2 for the spectral index distribution, and integrating over the desired flux interval and over all possible spectral indices, we can then calculate the collective diffuse emission due to unresolved sources of the “unidentified class” with fluxes between F_{\min} and F_{\max} . We will take $F_{\max} = 13 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ (the lower end of the “bright source” flux interval, where we assume that all sources with fluxes above this limit have been resolved by EGRET). F_{\min} (the low-flux limit of the flux-function extrapolation) is the free parameter in our calculation.

3 Results

Integrating Eq. (2) we can now calculate the contribution of unresolved unidentified sources to the diffuse background as a function of F_{\min} . Note that the overall level of the associated diffuse emission only depends on where the extrapolated power law breaks. The thick solid line in Fig. 1 shows the value of this cutoff so that the contribution of unidentified sources does not overtake the original EGRET estimate of the extragalactic gamma-ray background [3] in the range 100-300 MeV plus statistical error⁷. We would only need extrapolate the cumulative flux distribution for slightly more than an order

⁷ This is a conservative choice, since all more recent estimates of the extragalactic diffuse background give an EGRB level lower than the original estimate of [3]. If we had instead adopted a lower EGRB intensity, the thick solid line of Fig. 1 would move to higher fluxes, and this would make an impor-

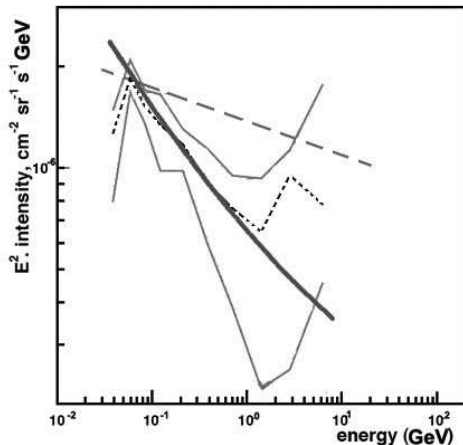


Fig. 3 Dashed line: Sreekumar et al. (1998) determination of the EGRB. Dotted line: Strong et al. (2004) determination of the EGRB (best guess). Solid lines: Strong et al. (2004) determination of the EGRB (systematics-based limits). Thick solid line: collective spectrum of unresolved unidentified sources (this work).

of magnitude below the lower limit of the resolved flux range to have unresolved unidentified sources comprise most of the extragalactic diffuse background, at least at low energies. This is not an extreme extrapolation, and therefore a significant contribution by the “unidentified” class to the diffuse background is likely.

Figure 3 shows the cumulative emission spectrum of unresolved unidentified sources, overplotted with the spectrum of the extragalactic diffuse emission derived from EGRET observations. The dashed line shows a single power-law fit to the Sreekumar et al. (1998) determination of the extragalactic gamma-ray background (EGRB) [3]. The dotted line is the more recent redetermination of the gamma-ray background by Strong et al (2004) [6], in which they used their more detailed model of the Milky Way diffuse emission to subtract the Galactic component from the EGRET diffuse sky map. The solid lines are the systematic uncertainties in the EGRB determination of [6], entering through their model of the Galaxy. Our calculation of the spectrum of the unresolved unidentified source component is shown with the thick solid line. At low energies, where the systematics are low, the unidentified component spectrum is in excellent agreement with the EGRB observational spectrum of [6]. At higher energies, where the systematics are large, the unidentified component spectrum is largely within systematics except at very high energies. If unidentified sources are indeed a dominant contribution at relatively low energies, then this result may be perceived as a tantalizing hint that at the highest energies of the EGRET range a new type of contribution, (e.g. from annihilating dark matter) may start to be important at a few tens of GeV.

tant unidentified source component of the EGRB even more likely.

4 Prospects for the GLAST era

The launch of GLAST in 2007 will provide us with significant new insight about the nature of unidentified sources and their possible contribution to the extragalactic diffuse background. The ideal solution to the unidentified source puzzle would be, of course, the direct positional association of all unidentified sources with undisputed low-energy counterparts. This would then allow us to build more confident models for the unresolved members of these classes of objects. However, such an outcome is unlikely, as the large number of possible counterparts and the large number of sources which we expect GLAST will be able to resolve make multi-wavelength campaigns for every single source impractical.

However, there is another definitive test that GLAST will be able to perform, which does not require confident identification of each source to provide information about the likely nature of unidentified sources as a population. With the increased flux sensitivity of GLAST, many more objects of the same class will be resolved. If these objects are mostly extragalactic, there will be an associated decrease of the extragalactic gamma-ray background from its EGRET levels, equal to the all-sky-averaged intensity of the newly resolved objects. The flux sensitivity of GLAST is expected to be about 50 times better than that of EGRET⁸. Therefore GLAST will be able to probe the flux distribution of unidentified sources down to fluxes close to F_{\min} and definitively test our empirical estimate.

If, on the other hand, these objects are mostly Galactic, then there will be an associated reduction of the Milky Way diffuse emission rather than of the isotropic background. For a discussion on a possible contribution of a large number of Galactic point sources to the Galactic diffuse emission and the role of such sources in explaining at least in part the origin of the GeV excess see [18].

5 Discussion

In this work, we have used a purely empirical model to explore the possibility that unresolved gamma-ray sources of the same class as unidentified EGRET sources have an appreciable contribution to the extragalactic gamma-ray background. We have argued that some unidentified source contribution to the gamma-ray background is guaranteed. We have additionally found that (1) if most unidentified sources are assumed to be extragalactic, we would only need the observed cumulative flux distribution of unidentified sources to extend without a break for a little more than one order of magnitude toward lower fluxes in order to have a very significant contribution to the gamma-ray background – at least at

⁸ <http://www-glast.stanford.edu/mission.html>

the lower part of the EGRET energy range; and (2) the spectrum of the cumulative emission of such unresolved sources would be very consistent with the observational determination of [6] of the gamma-ray background from EGRET data, within systematics.

We have learned that any model of the extragalactic gamma-ray background would be incomplete without some treatment of the unidentified source contribution. The results of our empirical model therefore motivate us to pursue specific population models for the unidentified sources. Although such models involve a more restrictive set of assumptions and increased uncertainties, they can provide more concrete predictions for the luminosity function of unresolved objects. Additionally, if we were to assume that the majority of unidentified sources are indeed members of a single, extragalactic class of gamma-ray emitters, and that unresolved members of this class do indeed contribute most of the extragalactic diffuse emission, then we can use simple evolution models to place limits on the redshifts of unidentified sources. We will pursue such models and calculations in an upcoming publication.

In this work we have tried, where possible, to make assumptions, which, if anything, *underestimate* the possible contribution of unresolved unidentified sources to the extragalactic diffuse background. However, some of our necessary working assumptions have the potential to overestimate the unidentified class contribution.

First of all, we have assumed that the majority of the sources belong in a single class. It is conceivable that instead, the resolved unidentified sources are a collection of members of several known and unknown classes of gamma-ray emitters. In this case, it is still likely that the summed contribution of unresolved members of all parent classes to the diffuse background is significant. However, the construction of a single cumulative flux distribution from all sources and its extrapolation to lower fluxes is no longer an indicative test for the importance of such a contribution.

Second, we have assumed that the majority of the sources we have used are extragalactic. It is not at all certain that this is indeed the case. The unidentified sources from the 3rd EGRET catalog [1] exhibit a strong concentration along the Galactic plane, and hence a significant fraction of the unidentified sources in the 3rd EGRET catalog are most likely Galactic. In the sample we have used, this feature is less pronounced (mainly because recent suggestions of possible low-energy counterparts refer mostly to Galactic plane objects). As a result, the possibility that *most* of the sources we have used in our calculations are extragalactic cannot be excluded on isotropy grounds. However, a *mostly* Galactic population originating in the disk and bulge is also consistent with constraints from the gamma-ray emission from nearby galaxies [19]. In this case the total luminosity of *resolved* unidentified sources is already a significant fraction of the total diffuse luminosity of normal galaxies. Consequently

the luminosity of each individual normal galaxy is significantly enhanced and the unidentified sources have a contribution to the extragalactic background through their hosts. Ultimately, the question of whether most unidentified sources are Galactic or extragalactic will be decided by GLAST.

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